MATLAB-BASED DESIGN AND ANALYSIS OF SMALL RICE TRANS-PLANTER IN HILLY AREAS
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基于 MATLAB 的丘陵地区小型水稻插秧机的设计与分析

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DOI: https://doi.org/10.35633/inmateh-73-09

Keywords: *Hilly Area, Rice Transplanter, Structural Design, Kinematic Analysis, Finite Element Analysis.*

ABSTRACT
A small-scale paddy rice transplanter for hilly and mountainous areas faces issues such as few suitable machines, poor transplanting results, and low adaptability and efficiency of large transplanters in small fields. To address these problems, a four-row small-scale paddy rice transplanter was designed, driven by an engine with chain transmission. The machine structure mainly consists of a frame, engine, paddy field wheels, seedling tray, transplanting mechanism, reversing gearbox, and electromagnetic clutch, with a total weight of only 50 kg, facilitating transportation and operation. MATLAB was used for kinematic simulation and analysis of the transplanting mechanism, plotting displacement diagrams of the seedling needles and motion characteristic curves of the transplanting mechanism. ANSYS software was employed for finite element analysis of key components to ensure they meet operational requirements. Experimental studies were conducted with transplanting speed as the experimental factor, using floating rate and missing insertion rate as test indicators. Results showed that under specified transplanting conditions, the floating rate stabilized at around 2.9% and the missing insertion rate at approximately 4.8%. These findings indicate that the designed small-scale transplanter can effectively meet the requirements for rice transplanting operations in hilly areas.

摘要
针对丘陵山区小地块的深泥脚田水稻种植机具少，插秧效果不佳，大型插秧机在小田块中适应性差、效率低等问题，设计了一款四行小型水稻插秧机，采用发动机驱动整机，链式传动。整机结构主要由机架、发动机、水田轮、秧盘和插秧机构、换向减速器和电磁离合器等组成，整机质量只有 50kg，方便转运与作业。利用 MATLAB 对插秧机构进行方仿真分析，并编程绘制出秧针的位移图和插秧机构的运动特性曲线；利用 ANSYS 软件对关键部件进行有限元分析，确保所设计的零部件能满足使用要求；以漂秧率和漏插率为试验指标，插秧机前进速度为试验因素，进行试验研究，得到插秧机在规定范围内插秧作业时，漂秧率基本稳定在 2.9%左右，漏插率基本在 4.8%左右。结果表明，所设计的小型插秧机能够基本满足丘陵地区的水稻插秧作业。

INTRODUCTION
As one of the essential food crops for human beings, rice has a relatively long history of cultivation and consumption, and more than half of the world's population consumes rice. China is the country with the most extended history of rice cultivation in the world, planting rice as early as six or seven thousand years ago, and is currently the world's first rice-producing country *(Cai et al., 2017; Lou et al., 2020; Hafijur et al., 2022)*. In recent years, with the development of agricultural mechanization, rice transplanter has gradually replaced the traditional manual planting method *(Chen et al., 2022; Li et al., 2022; Yang et al., 2024)*. Compared with artificial planting, mechanized rice trans-planting can better control plant spacing and transplanting depth, which is conducive to the growth and management of seedlings in the later stage, and ensures both trans-planting efficiency and quality *(Fu et al., 2023; Hu et al., 2024; Kumar et al., 2023)*.

Hilly areas have complex terrain, fragmented fields, significant height differences, in-convenient road access, centralized large-scale production organization difficulties, agricultural machinery and agronomic technology mismatches, and the existing rice trans-planting equipment can't meet the high-speed development of large-area mechanized rice production in hilly areas. Therefore, there is a need for more customized small rice transplanting machines that adapt to the characteristics of hilly terrace fields.

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In 2022, Li et al. designed a small impeller energy-taking rice transplanter in a labor-saving operation, carried out a detailed optimization design for the transplanting mechanism of the box mechanism, and analyzed and evaluated the key components by using finite element simulation *(Li et al., 2022)*. In 2022, Mao G. et al. carried out a comparative field experiment between a light and simple rice transplanter and a small-scale direct seeding rice transplanter in hilly mountainous areas, and concluded that light and simple rice transplanter and small-scale rice direct seeding machine can't meet the high-speed development of large-scale mechanized rice production in hilly terrace fields using the structure of the machine, the production efficiency, and the rice yield of three aspects. Comparison and analysis of light type rice transplanter is more suitable for rice cultivation in hilly mountainous areas *(Mao et al., 2022)*.

In this paper, given the dilemma of rice transplanter in hilly areas facing no "excellent machine" available, a 2ZQS-4 four-row small rice transplanter is designed to provide reference and reference for the design of rice transplanter in hilly areas.

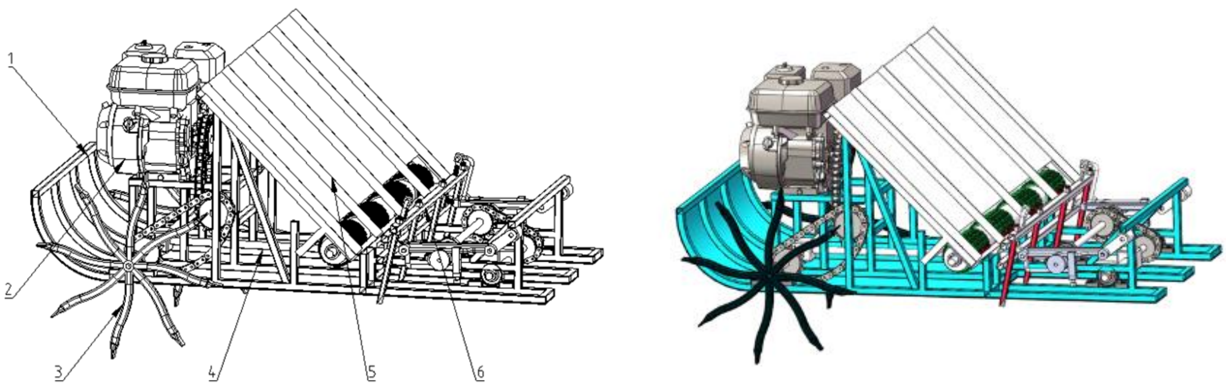
MATERIAL AND METHODS

STRUCTURAL DESIGN

The overall structure and working principle

The overall structure of the 2ZQS-4 rice transplanter is shown in Fig.1A. It mainly consists of frame *1*, engine *2*, paddy wheel *3*, transmission system *4*, seedling tray *5* and rice transplanter mechanism *6*. When working in the field, the rice transplanter power is provided by engine *2*, the engine output power is transmitted to the paddy wheel *3* through the commutation reducer, and the axle transmits the power synchronously to the rear rice seedling plate *5* and the transplanting mechanism 6 through the commutation reducer to ensure that the rice transplanter realizes the synchronization of the power during the operation. The rice-planting mechanism adopts a crank-rocker type mechanism, and the input and output end of the paddy wheel axle are respectively equipped with electromagnetic clutches, which control the rice-planting and travelling operations of the rice-planting machine through the clutches.

Because the operation process of rice transplanter is more complicated, the rice transplanting operation needs the forward speed, the left and right moving speed of the seedling box and the rotary movement of the rice transplanting mechanism to cooperate with each other in order to accurately and correctly take down the seedlings and insert them into the paddy field, so all the parts of the whole machine's power are supplied by the gasoline engine, and the operation of the rice transplanter is controlled by the ratio between the reducer and the transmission chain *(Xu et al., 2022; Zhu et al., 2023)*. Moreover, the seedling needles are fastened to the seedling needle holder by bolts so that the depth of rice transplanting can be adjusted, and the corresponding tilt angle of the seedling needle holder can be adjusted to ensure that the needles can pick up the rice seedlings smoothly. The three-dimensional model diagram of the rice transplanter is shown in Fig. 1B.



(A) Schematic diagram *(B) 3-D model diagram*

Fig. 1 – The overall structure of 2ZQS-4 rice transplanter

1-frame; 2-engine; 3-paddy wheel; 4-transmission system; 5-rice paddy; 6-rice transplanter mechanism.

The transmission system design

The transmission system of the 2ZQS-4 rice transplanter as a whole is shown in Fig. 2, which mainly consists of an engine, reversing reducer, transmission sprocket, transmission shaft, electromagnetic clutch, etc.

The power of the whole machine is provided by engine *8*, and the power of the rice transplanter is matched with each other in terms of the forward movement of the rice transplanter, the movement of the seedling box, and the operation of the rice transplanting mechanism, so as to ensure that the rice transplanter can pick up the rice seedlings smoothly in its operation, and that the transplanting distance of the rice seedlings is 150 mm.

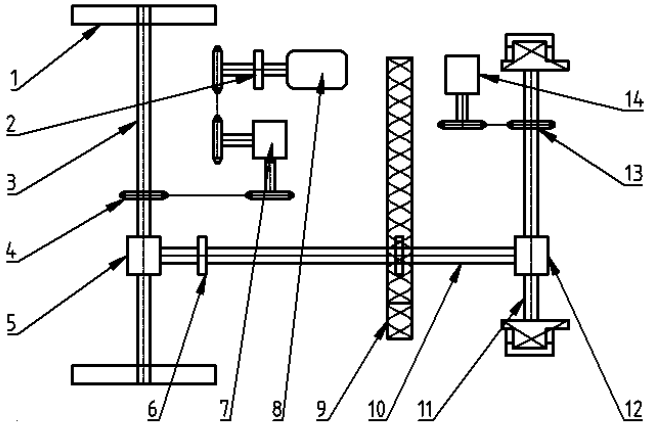


Fig. 2 – 2ZQS-4 rice transplanter transmission system schematic diagram
1-Paddy wheel; 2-Electromagnetic clutch; 3-Wheel shaft; 4-Sprocket; 5-Reversing reducer; 6-Electromagnetic clutch; 7-Reversing reducer; 8-Engine; 9-Seedling box; 10-Main drive shaft; 11-Transplanting mechanism drive shaft; 12-Reversing reducer; 13-Sprocket; 14-Transplanting mechanism.

In order to make the rice transplanter work smoothly in the deep mud foot field, the design of its wheel diameter is 800 mm, then the rice transplanter wheel rotates for one week, and the forward displacement of the machine S calculation formula is shown in the equation (1).

$$S = \pi D \tag{1}$$

It was calculated that S=2513.27 mm.

There is a slight loss in transmission efficiency because the wheel slips in the paddy field, and the power is transmitted to the crank of the rice-planting mechanism through the reducer and chain *(Cai et al., 2012; Kumar et al., 2021)*. So, the wheel rotates for one week, and the number of rice transplanting times M is calculated as shown in equation (2).

$$M = \frac{S\eta}{N} \tag{2}$$

where: M - Number of rice planting, (times);

H -Total efficiency, (η=80%);

N - plant spacing, (N=150 mm);

Calculated M = 13. That is, the wheel rotates for one week, the rice transplanter inserts seedlings 13 times, and the forward speed of the rice transplanter is set at 0.5 m/s, then the crank rotation speed of the rice transplanter mechanism can be obtained as 3.25 r/s.

Main technical parameters

The main technical parameters of the rice transplanter are shown in Table 1.

Table 1

Main technical parameters of 2ZQS-4 rice transplanter

Parameter Name	Parameter Value
Model	2ZQS-4
Rated engine power/(kW)	3.3
Rated engine speed/(r/min)	3600
Overall dimensions (L×W×H)/(mm)	1500×1200×1200
Operating speed/(m/s)	0.25~0.75
Number of rice-planting rows/(row)	4
Diameter of paddy wheel/(mm)	800
Row spacing/(mm)	300
Plant spacing/(mm)	150
Transplanting box length/(mm)	600
Transplanting mechanism type	Crank Rocker

KINEMATICS SIMULATION ANALYSIS OF RICE TRANSPLANTER MECHANISM

The mathematical model

The principle of the rice-planting mechanism is shown in Fig. 3, the crank AD rotates around the rotary center A, the rocker BC is hinged on the frame AB, the connecting rod CD is hinged on BC and AD respectively, the seedling needle EF is fixed on the connecting rod CD. The CDEF forms a fixed quadrilateral structure, and the tip of the seedling needle is the F point. When working, the crank rotates around point A uniformly, driving the seedling needle to realize the seedling picking and inserting operation.

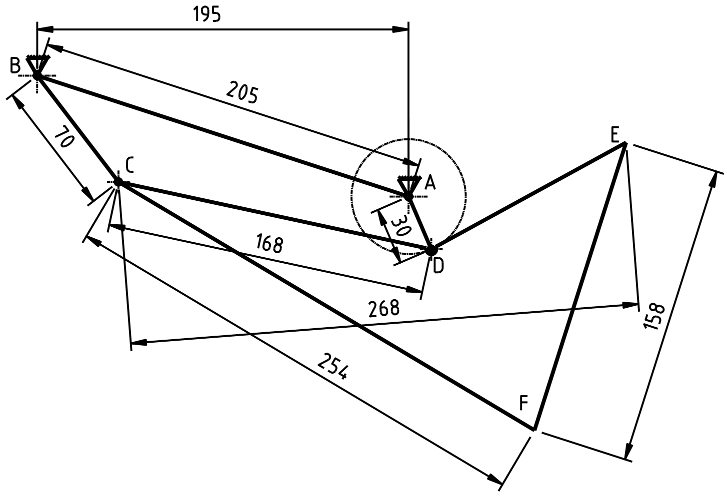


Fig. 3 – Schematic diagram of rice-planting mechanism

The closed-loop vector diagram of the rice planting mechanism is shown in Fig. 4, and the right-handed right-angle coordinate system is established with the crank rotation center as the coordinate origin.

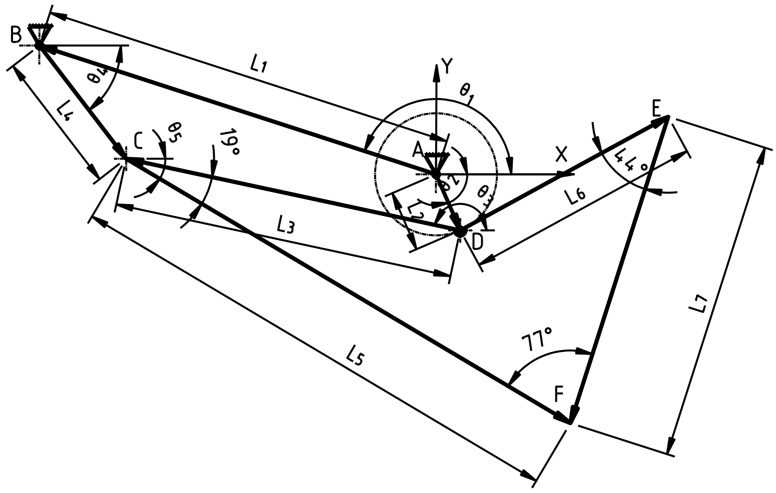


Fig. 4 – Closed-loop vector diagram of rice-planting mechanism

Establish the vector equation of the mechanism, as shown in equation (3).

$$\vec{l_1} + \vec{l_4} = \vec{l_2} + \vec{l_3} \tag{3}$$

Decomposing the above vector equation into x and y coordinate axes gives the displacement equation, as shown in equation (4).

$$\begin{cases} l_1 \cos\theta_1 + l_4 \cos\theta_4 = l_2 \cos\theta_2 + l_3 \cos\theta_3 \\ l_1 \sin\theta_1 + l_4 \sin\theta_4 = l_2 \sin\theta_2 + l_3 \sin\theta_3 \end{cases} \tag{4}$$

Derivation of the above displacement equation concerning time yields the velocity equation, the matrix form of which is given in equation (5).

$$\begin{bmatrix} -l_3 \sin\theta_3 & l_4 \sin\theta_4 \\ l_3 \cos\theta_3 & -l_4 \cos\theta_4 \end{bmatrix} \begin{bmatrix} \omega_3 \\ \omega_4 \end{bmatrix} = \begin{bmatrix} l_2 \sin\theta_2 \omega_2 \\ -l_2 \cos\theta_2 \omega_2 \end{bmatrix} \tag{5}$$

Derivation of the velocity equation concerning time yields the acceleration equation, the matrix form of which is given in equation (6).

$$\begin{bmatrix} -l_3\sin\theta_3 & l_4\sin\theta_4 \\ l_3\cos\theta_3 & -l_4\cos\theta_4 \end{bmatrix}\begin{bmatrix}\alpha_3 \\ \alpha_4\end{bmatrix}=\begin{bmatrix} l_2\sin\theta_2\alpha_2+l_2\cos\theta_2\omega_2^2+l_3\cos\theta_3\omega_3^2-l_4\cos\theta_4\omega_4^2 \\ -l_2\cos\theta_2\alpha_2+l_2\sin\theta_2\omega_2^2+l_3\sin\theta_3\omega_3^2-l_4\sin\theta_4\omega_4^2 \end{bmatrix} \quad (6)$$

The displacement equation for point F of the seedling tip is shown in equation (7).

$$\begin{Bmatrix} X_F=l_1\cos\theta_1+l_4\cos\theta_4+l_5\cos\theta_5 \\ Y_F=l_1\sin\theta_1+l_4\sin\theta_4+l_5\sin\theta_5 \end{Bmatrix} \quad (7)$$

Derivation of the displacement equation gives its velocity equation, as shown in equation (8).

$$\begin{Bmatrix} X'=-l_4\sin\theta_4\omega_4-l_5\sin\theta_5\omega_5 \\ Y'=l_4\cos\theta_4\omega_4+l_5\cos\theta_5\omega_5 \end{Bmatrix} \quad (8)$$

Derivation of the velocity equation gives its acceleration equation, as shown in equation (9).

$$\begin{Bmatrix} X''=-l_4\cos\theta_4\omega_4^2-l_4\sin\theta_4\alpha_4+l_5\cos\theta_5\omega_5^2-l_5\sin\theta_5\alpha_5 \\ Y''=-l_4\sin\theta_4\omega_4^2+l_4\cos\theta_4\alpha_4-l_5\sin\theta_5\omega_5^2+l_5\cos\theta_5\alpha_5 \end{Bmatrix} \quad (9)$$

From the above schematic and vector diagram:

$$\theta_5=-\left(180^\circ-\left(\theta_3-19^\circ\right)\right) \quad (10)$$

Simulation Model

The Simulink kinematic simulation model is established based on the above mathematical modelling program, as shown in Fig. 5. The simulation initial condition table is shown in Table 2 *(Kumar et al., 2022; Li, 2024)*.

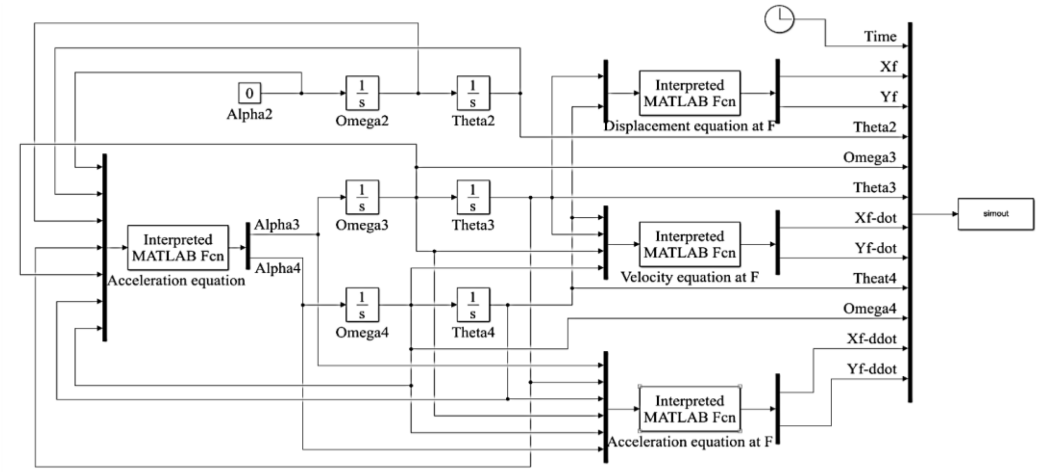


Fig. 5 – Simulink simulation model diagram

Table 2

Simulation initial condition table

Parameter Name	Parameter Value
l_1 / (mm)	205
l_2 / (mm)	30
l_3 / (mm)	168
l_4 / (mm)	70
l_5 / (mm)	254
θ_1 / (rad)	2.8274
θ_2 / (rad)	-1.1694
θ_3 / (rad)	2.9322
θ_4 / (rad)	-0.9076
ω_2 / (rad/s)	-20.42
ω_3 / (rad/s)	1.4682
ω_4 / (rad/s)	-11.1526
Machine forward speed / (m/s)	0.5
Simulation time / (s)	1

RESULTS

Simulation results and analysis

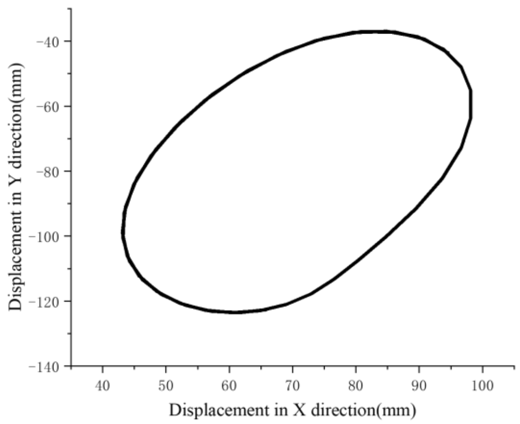
Through simulation, the displacement of the tip of the seedling needle at point F is shown in Fig. 6A. The seedling needle does regular periodic movement, and basically becomes parallel with the seedling tray when picking up seedlings at the front end so as to avoid injuring seedlings to the maximum extent. To effectively insert seedlings into the ground and lower the rate of drifting and floating seedlings, the seedling needle must be essentially in a vertical position after being picked up *(Ma, 2023)*.

From the simulation results, the horizontal and vertical velocity change rule of the rice-planting mechanism is shown in Fig. 6B and Fig. 6C. The velocity change range of the horizontal direction is -0.44m/s~0.60m/s, and the velocity change range of the vertical direction is -0.94m/s~0.87m/s. The rice-planting mechanism's motion is a stable periodic simple harmonic motion.

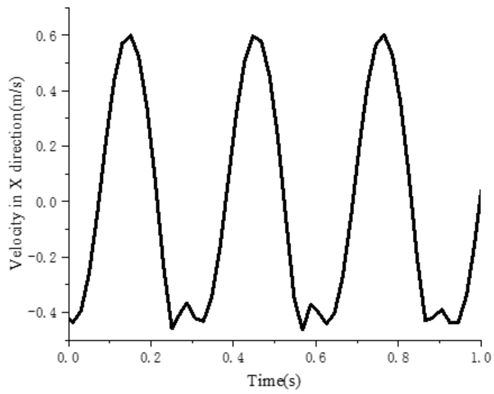
From the simulation results, the acceleration change rule of the horizontal and vertical direction of the rice-planting mechanism is shown in Fig. 6D and Fig. 6E. The acceleration change range of the horizontal direction is -6.17m/s^2~18.70m/s^2, and the acceleration change range of the vertical direction is -20.64m/s^2~13.98m/s^2. The rice-planting mechanism's motion is a stable periodic simple harmonic motion.

From the simulation results, the angular velocity change rule of the transplanting mechanism is shown in Fig. 6F. The angular velocity change range is -5.55rad/s~3.61rad/s. The angular velocity of the transplanting mechanism is a stable cyclic change. There will be no considerable vibration in the process of the movement, and it can stably carry out the transplanting operation, prolonging the service life of the whole rice transplanter.

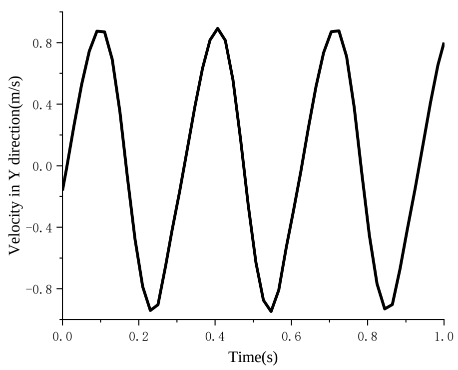
Through the kinematics simulation of the rice-planting mechanism and simulation of its complex motion process, its motion characteristics can be more intuitively analyzed, thus providing a reference for the subsequent dynamics analysis, finite element simulation, test and optimization design.



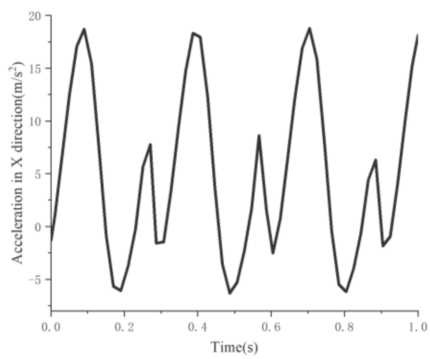
(A)



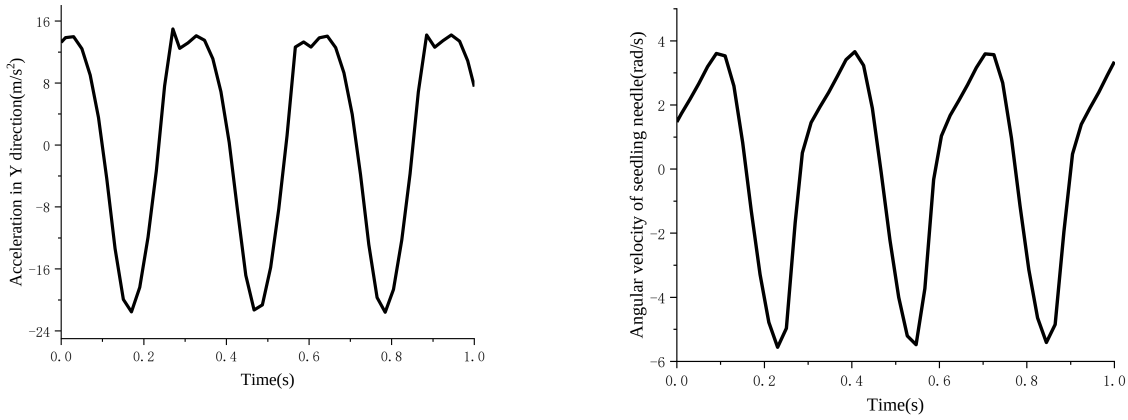
(B)



(C)



(D)



(E) (F)

Fig. 6 – Kinematic simulation analysis results

A-Displacement diagram of F point of the tip of seedling needle; B-Variation of horizontal velocity of rice interpolation mechanism; C-Variation of vertical velocity of rice interpolation mechanism; D-Accelerating change of horizontal velocity of rice transplanting mechanism; E-Accelerating change of vertical direction of rice transplanting mechanism; F-Angular velocity change rule diagram of rice-planting mechanism.

FINITE ELEMENT SIMULATION ANALYSIS

Through the above kinematic analysis and observation of actual operating conditions, in the rice transplanter machine, in terms of strength and stiffness, what is the most prone to fracture is the crank of the rice transplanter mechanism, so using ANSYS to analyze the finite element of the crank, study its stress, strain and deformation will lay a foundation for the development of the rice transplanter machine at a later stage *(Wen et al., 2019; Zhang et al., 2021)*.

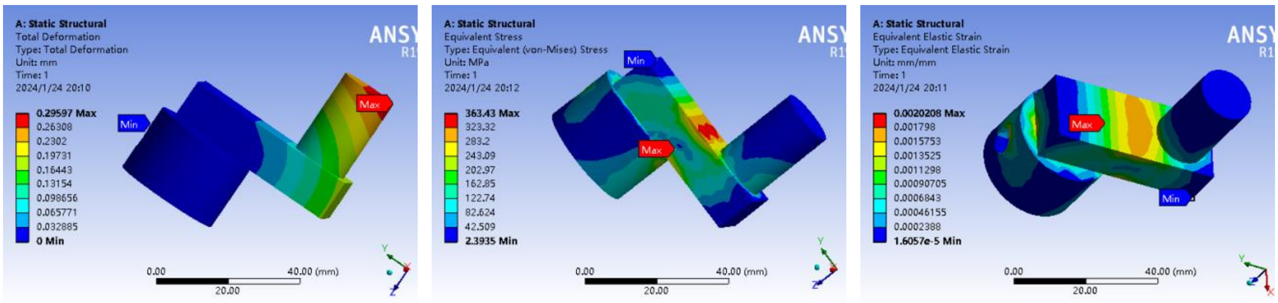
Simulation model

After three-dimensional modeling by using SolidWorks software, it is imported into Workbench, and the selected material of the crank is Hardened 45 Steel *(Zhang et al., 2021)*. After importing it into the software, meshing is carried out with tetrahedral cells as the primary type, boundary conditions and constraints are set, and the maximum force obtained through dynamics analysis is applied to it.

Simulation results and analysis

After finite element analysis, the total displacement analysis of the crank can be obtained as shown in Fig. 7A, from which it can be seen that the displacement change at any point out of the crank is minimal, and the displacement change at the maximum is only 0.295 mm.

The stress analysis cloud diagram of the crank is shown in Fig. 7B, and the strain analysis cloud diagram is shown in Fig. 7C; the maximum stress suffered by the crank is 363.43 MPa, and the maximum strain is 0.002, the yield strength of 45 steel is 355 MPa, and the tensile strength is 6000 MPa, so it can be seen that the crank designed meets the needs of use completely.



(A) (B) (C)

Fig. 7 – The result of finite element simulation

A-Crank total displacement analysis cloud diagram; B-Crank stress analysis cloud; C-Crank Strain Analysis.

EXPERIMENTAL RESEARCH

Blanket seedlings cultivated in 3-inch trays were used for transplanting tests in winter paddy fields, and the drift rate and leakage rate in the selected range were measured by varying different forward speeds of the rice transplanter and selecting a length of 5 meters at the same speed *(Luo et al., 2020)*. Each set of tests was repeated three times, and the results were averaged. The drift and leakage rates' formulas are shown in equation (11). The test results are shown in Table 3.

$$P = \frac{Z_P}{Z} \times 100\% \qquad L = \frac{Z_L}{Z} \times 100\% \tag{11}$$

where:

P - Drift seedling rate, (%);
L - Leakage rate, (%);
Z_P - Total number of drifted rice plants, (plants);
Z_L - Total number of missed insertions, (plants);
Z - Total number of transplanted seedlings, (plants).

Table 3

Table of test results

Transplanter forward speed（m/s）	Drift seedling rate（%）	Leakage rate（%）
0.3	2.95	4.67
0.4	2.93	4.78
0.5	2.91	4.83
0.6	2.96	4.88
0.7	3.12	5.51

From the above test results, it can be seen that the rice transplanter will increase the drift rate and leakage rate as the forward speed increases. The main reason is that, with the increase in forward speed, the frequency of transplanting will also increase, which leads to the seedling needle entering the next action before the seedlings are stabilized, and the seedling box can't move in time to send the seedlings to the designated position. However, the overall test results show that the rice transplanter can meet the corresponding national standards.

CONCLUSIONS

In this paper, for the problem of lack of rice transplanter in deep mud foot fields in hilly and mountainous areas, a 2ZQS-4 four-row small rice transplanter is designed, with a row spacing of 300 mm and plant spacing of 150 mm, and the transplanting mechanism adopts a crank-linkage structure, which makes the whole machine compact and lightweight. It is very suitable for transplanting rice seedlings in small plots of land in hilly and mountainous areas.

The kinematic simulation of the rice-planting mechanism shows that when the rice-planting machine operates within the predetermined speed range, the movement is stable, and there is no violent vibration, which meets the requirement of stability. The rice-planting operation can be carried out safely and effectively in the field. The finite element analysis of the key components shows that the whole machine structure is reasonably designed, and the materials selected can meet the strength and stiffness of use.

The field test results of the rice transplanter show that when the rice transplanter operates within the designed forward speed, the rate of drifting rice seedlings is basically maintained at about 2.9%, and the rate of leakage is stabilized at about 4.8%, which can meet the relevant standards.

In summary, the four rows of small rice transplanter can meet the requirements of rice transplanter operation in small plots in hilly mountainous areas, and the whole machine is reasonable in design and stable in structure, which can provide a certain reference value for the design and development of rice transplanter in hilly areas.

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